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Methods and tools to evaluate the availability of renewable energy sources

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ABSTRACT

The recent statements of both the European Union and the US Presidency pushed in the direction of using renewable forms of energy, in order to act against climate changes induced by the growing concentration of carbon dioxide in the atmosphere. In this paper, a survey regarding methods and tools presently available to determine potential and exploitable energy in the most important renewable sectors (i.e., solar, wind, wave, biomass and geothermal energy) is presented. Moreover, challenges for each renewable resource are highlighted as well as the available tools that can help in evaluating the use of a mix of different sources.

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1. Introduction

As we all know, there is basically only one source of energy for us, living on the Earth: the sun. The power it irradiates on our planet is estimated to be about 175,000 TW, four orders of magnitude more than the power we use even in our energy intensive times.

The energy we have received and continue to receive from the sun is converted in many different ways by the dynamics of our planet and of its atmosphere: the high temperatures below the crust are due to its original activity; the presence of hydrocarbons in the soil, to ancient photosynthesis; winds and waves to the present thermal differences.

Thinking to a horizon of few tens of years, the current solar activity and the primordial heat left inside the planet may be assumed as constant and thus represent the unique renewable sources of energy for mankind.

We have however several different ways for transforming this energy into forms that are more suitable for our everyday use. The mechanical energy of winds, water and waves can be converted into electricity so that it can be easily shipped far from the source (and we are not forced any more to bring our grain to the windmills as centuries ago). Biomass resources, which are the product of biological processes induced by solar light, can be burned to produce heat (to be used either as such or again to produce electricity) or chemically or biologically processed to generate usable fuels. The sunlight can be used directly to produce heat in a more usable form or can drive electron movements in silicon cells to produce electricity. A renewable energy source, freshwater, has been indeed the first way of producing electricity and has been extensively studied and exploited all over the world since more than one century. This is why it will not be further analysed in this paper.

All the options we have to extract energy from solar activity enjoy the advantage of being sustainable (they can be replicated in time, at least over a horizon of several years) and to alter only marginally the carbon balance of the planet's atmosphere, because the production, use, and decommissioning of conversion plants involve some emission that is normally small in comparison to those involved in the production of the same energy by fossil fuels. The use of fossil fuels on the contrary is both unsustainable (they are present in the Earth in finite quantities) and increases the amount of CO_2 in the atmosphere by releasing the carbon absorbed by vegetation millions of years ago and presently stored into the soil.

On the other hand, all the renewable forms in which we exploit the sun energy are characterized by being spatially distributed and lacking the huge reservoirs of fossil fuels or freshwater, that can easily compensate for the time differences between offer and demand of energy. So the exploitation of these sources of energy is somehow more complex, and they are sometimes referred as "intermittent sources".

Their spatial distribution also means that their exploitation is closely linked to the peculiar characteristics of the local environment and, in turn, it may have environmental impacts distributed on a wider area.

A characteristic they share with fossil energy sources is the impossibility of converting and exploiting all the energy which is potentially available. We can thus distinguish three different values:

- potential energy, that is the gross energy of the source (e.g. that of wind at a given location);
- theoretical energy, that is the fraction that can be harvested by the energy conversion system (e.g. the solar radiation collected by a certain surface of solar panels);
- exploitable energy, the fraction that can be used taking into account criteria of sustainability related to logistic, environmental and economic issues (e.g. the heat produced by a biomass fueled plant).

These definitions may be interpreted in a slightly different way for different applications. In many cases, for instance, the electric output of a plant can be considered as representing the exploitable energy. However, if we are talking of an offshore wind farm, 20 km from the rest of the grid, perhaps we want to compute the electric

energy net from the (non-irrelevant) losses on the underwater connecting cable.

Despite the technological and logistic difficulties, the attention toward these renewable forms of energy is steadily increasing all over the world, due to the urgency to act against climate changes induced by the growing concentration of carbon dioxide in the atmosphere. The recent statements of both the European Union and the US Presidency pushed in this direction.

As an example, the European Union set an overall binding target of a 20% share of renewable energy sources in energy consumption and a 10% binding minimum target for biofuels in transport to be achieved by each Member State by 2020. Reaching this target will need a consistent proactive attitude of all governments, since in 2006 renewable energies were estimated at 6.92% of the primary energy consumption of the EU countries, and at 14.6%, mainly hydropower, of the electricity production.

This is why it is worth to revise methods and tools presently available to determine potential and exploitable energy in the most important renewable sectors, as done in this paper.

In the next sections, we will thus survey the state of the art of evaluation approaches for solar, wind, wave, biomass and geothermal energy, with attention to the site specific environmental characteristics, but without dealing with the final conversion step. Though this must be kept in mind because it sometimes influences the amount of exploitable energy, a review of possible conversion devices and processes would go far beyond the scope of this paper.

2. Solar resource potentials

Today, the most common technologies for utilising solar energy are photovoltaic and solar thermal systems. One of the main influencing factors for an economically feasible performance of solar energy systems (besides of installation costs, operation costs and lifetime of system components) is the availability of solar energy on ground surface that can be converted into heat or electricity [1]. Therefore precise solar irradiation data are of utmost importance for successful planning and operation of solar energy systems. Solar irradiation means the amount of energy that reaches a unit area over a stated time interval, expressed as Wh/m^2 [2]. Solar radiation can be divided into direct and diffuse radiation. Together these components are denoted as global irradiation. The distinction between direct and diffuse radiation is important as different technologies utilise different forms of solar energy.

2.1. Identification of solar energy potentials

For the estimation of available renewable energy, a top down approach is widely used [3–6], which can also be applied in the case of solar energy. The top down approach starts with the computation of an available solar energy potential. This is expressed as the physically available solar radiation on the earth's surface, that is influenced by various factors, as described in Suri and Hofierka [2]. These factors are the earth's geometry, revolution and rotation, the terrain in terms of elevation, surface inclination and orientation and shadows as well as the atmospheric attenuation due to scattering and absorption by gases, solid and liquid particles and clouds. The estimated potential is then reduced by considering technical limitations (e.g. conversion efficiency factors), which means taking into account the losses associated with the conversion of solar irradiation to electric power or heat by state of the art technologies.

By including rather soft factors which may be modified over time and may vary regionally (e.g. acceptance of technology, legislation) the potential is further reduced to realisable energy (Fig. 2.1) [3]. For the estimation of solar energy potential, this top down approach can be adopted at different scales (global, continental or local).

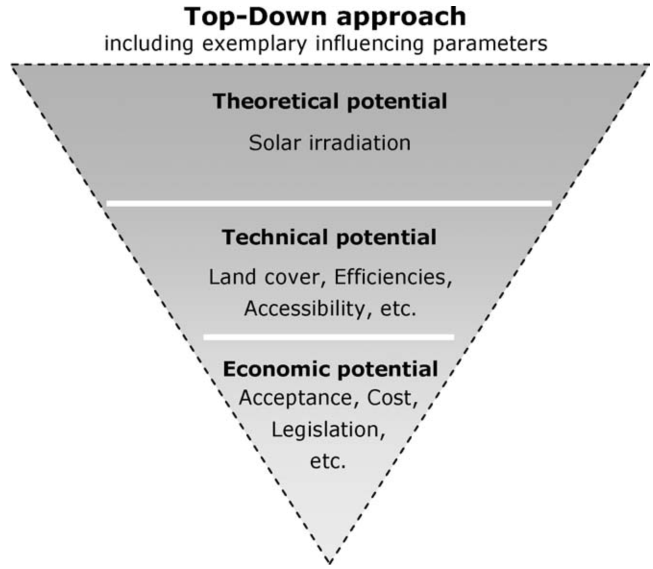

Fig. 2.1. Top-down approach to estimate renewable energy potentials [3,19].

Several databases on solar radiation exist, employing different approaches and methods to identify potential, theoretical, and exploitable energy as described in Section 2.2. The restricting factors included to derive the theoretical and exploitable levels may vary with the spatial resolution, as some of them can only be computed on fine scales.

2.2. Approaches for estimating solar energy potential

There are different approaches to estimate solar irradiation on ground surface. A first approach is based on in situ data, a second method derives solar radiation data from satellite data, and, finally, a third is a combination of both.

The spreading of meteorological stations which measure solar radiation is very heterogeneous over the planet and some regions are not covered properly. Therefore, in many regions solar irradiation cannot be accurately represented by meteorological stations. Other measured data, like sunshine duration or cloud cover, are used for the estimation of solar radiation in these cases. Additionally, most stations only measure global irradiation. Only few stations measure diffuse solar radiation separately and thus the diffuse fraction has to be estimated by empirical models in many cases. To derive continuous spatial datasets from the available heterogeneously measured or estimated data, interpolation techniques are applied [7]. A 3D inverse distance interpolation model for instance, is used within the Meteonorm database for the derivation of monthly values of global radiation between the single measurement stations [8]. In most cases, solar radiation data derived with this approach are available as daily total or monthly averages and only in few cases hourly or more detailed data are available. Especially in regions with complex topography (e.g. mountain regions) the uncertainty of datasets derived by spatial interpolation of ground measured data is high [7].

The use of satellite data to estimate solar radiation values represents the second approach. Satellite images from geostationary satellites like Meteosat, GOES, MSAT or MSG (Meteosat Second Generation) can be used to derive information on solar irradiance over vast areas. Improvements have been made in the last years regarding spatial and temporal resolution of these data. While the spatial resolution for the Meteosat satellite is 2.5 km [7,9] and the

temporal resolution is 30 min, the new generation of satellites (e.g. MSG) can provide data at a temporal resolution of 15 min and a spatial resolution of 1 km [10,11]. Rigollier et al. [12], in agreement with other authors, points out that, for satellite data with pixel sizes of 10 km, the assessment of solar irradiation provides more precise values compared to results of estimates by interpolation of measurements from meteorological stations as soon as the distance between the stations is greater than 34 km for hourly irradiation values, and 50 km for daily values. A widely used method within this approach is the Heliosat method, which was originally implemented by Cano et al. [13] and modified by Beyer et al. [172] and Hammer [10,177]. The method has been further improved by Rigollier et al. [12], implementing the Heliosat2 method. The software for Heliosat2 is freely available at www.helioclim.net. The latest evolution, Heliosat3, is presented in Mueller et al. [178] and Betcke et al. [14].

The third and most frequently applied approach uses measurements from meteorological stations as well as satellite data. Satellite derived data are used for areas with an unsatisfactory spreading of meteorological stations, as done in the Meteonorm database [8] or in the PVGIS (see below) approach.

There are several databases presenting solar radiation data for different extents (global, continental). The list shown in Table 2.1 is not exhaustive but shows a selection of databases for global, cross continental and European extents. Input is taken from Suri et al. [11], who have compared several of the existing databases on solar radiation. Beside the differences regarding the extent and the general methodological approach, also the calculation of primary and derived parameters on solar radiation as well as the temporal and spatial resolution differs between the databases. In the following, three representative databases are described in more detail.

The *Meteonorm database* [8] is based on a 3D inverse distance interpolation of measurements of solar radiation data from meteorological stations and includes data on global solar radiation as well as the direct and diffuse fraction on a global extent. Satellite data are used for areas with a low density of meteorological stations. The time resolution for interpolated measurement data is a month. Hourly and minute values can be generated from monthly average values using stochastic models. Global and diffuse radiation on inclined surfaces including skyline effects can be calculated, in addition to horizontal surfaces. Influences of terrain shadowing are already included. The time period covered is 1981–2000. The database is a licensed product and is available for purchase at www.meteonorm.com.

The *PVGIS* (Photovoltaic Geographic Information System) [1,15] database includes monthly averaged values of solar radiation and ambient temperature for Europe. It processes climatologic data that are available within the European Solar Radiation Atlas by using interpolation techniques and the r.sun model. This model is implemented in GRASS GIS, an open source environment based on C programming language. With the model, direct, diffuse and reflected fractions of solar irradiation can be calculated for horizontal and inclined surfaces. The model also considers shadowing due to local terrain features, by integrating a digital elevation model. The spatial resolution of the derived raster maps is 1 km × 1 km. Further improvements for global radiation estimates of the model can be achieved by the integration of a 100 m resolution digital elevation model [11,16]. Data are freely accessible at http://re.jrc.ec.europa.eu/pvgis/.

The *HelioClim 2/3 databases* contain long time series of solar radiation data for Europe and Africa. Meteosat satellite images are used to derive global irradiation maps on a horizontal surface [17]. The estimations are based on the Heliosat2 method [12], whose software is freely accessible at www.helioclim.net. With the Helioclim3 database, the temporal and spatial resolution could be

Table 2.1
Databases on solar irradiation and methods (Input taken from [11]).

Database/method	Extent	Technical parameters				Methods used in calculation of primary and derived parameters				
		Data inputs	Period	Time resolution	Spatial resolution	Global horizontal radiation	Diffuse fraction	Inclined surface (diffuse model)	Derived parameters*	For PV/ST potential estimation**
PVGIS (Europe)	Europe	~560 meteo stations	1981–1990	Monthly averages	1 km × 1 km + on-fly disaggreg. by 100 m DEM	3D spline interpol. of ground data + model r. sun: [2]	Measured at 63 stations, rest estim. by Czeplak (1996)	Muneer [179]	G, D, terrain shadowing (beam only)	PV, ST
Meteonorm 6.1	Global	Meteo stations + satellite data	1981–2000	Monthly averages	Interpol. (on-fly) + satellite; disaggreg. by 100 m DEM	3D inverse distance interpol. Heliosat 1 for sat. data	Perez et al. [181]	Perez et al. [180]	G, D, B, terrain shadowing (beam and diffuse)	PV, ST
ESRA	Europe	~560 meteo stations + SRB satellite data	1981–2000	Monthly averages	5 arc-min × 5 arc-min	Interpol. of ground data by co-kriging: Beyer et al. [173]	Measured at 63 stations, the rest estim. by Czeplak (1996)	Muneer [179]	G,D,B, clearness, zones	PV, ST
Satel-Light	Europe	Meteosat 5, 6, 7	1996–2000	30-min	4.6–4.2 km × 6.1–14.2 km	Heliosat 1 (Dumortier diffuse clear sky model)	Skartveit et al. [184]	Skartveit and Olseth [183]	G,B,D, illuminances, ext. statistics	PV, ST
HelioClim-2	Cross-continental	Meteo sat 8 and 9 (MSG)	2004–2007	15-min	3.1–4.2 km × 4.1–9.6 km	Heliosat-2 [12]	N/A	N/A	G	PV
NASA SSE 6	Global	GEWEX/SRB 3 + ISCCP satel. Clouds + NCAR reanalysis	1983–2005	3-h	1 arc-degree × 1 arc-degree	Satellite model by Pinker and Laszlo [182]	Erbs et al. [176]	Retscreen method by Duffie and Beckman [175]	G,B,D, extended number of parameters and statistics	PV, ST

* G = global, B = beam (direct), D = diffuse radiation.
** PV = photovoltaic, ST = solar thermal.

enhanced thanks to the new Meteosat Second Generation satellites [10]. The Helioclim3 database has a temporal resolution of 15 min and a spatial resolution of approximately 5 km. Data are available from 2004 to 2007 [18].

2.3. Estimation of exploitable solar potential

Following the described top down approach, the available solar potential is further reduced to what is economically exploitable, by the integration of restricting factors regarding suitable areas, technical and economical factors ([5,6,19]). Geographical restrictions for the installation of solar energy systems are included to derive only suitable areas, by using land cover maps. This evaluation also depends on the type of solar installations. Hoogwijk [5] shows how to identify suitable areas for centralised and decentralised PV systems. While centralised installations with grid connection are assumed to be installed on land surface, decentralised applications are assigned to roofs or facades. Concentrating Solar Power (CSP) for instance is most suitable in bare areas with a high share of direct irradiation. On a global or regional scale, current land cover datasets are satisfactory for the estimation of suitable areas, on a local scale, analyses may require to go down to the single roof top. One approach for the estimation at such a detailed level is the use of Laserscan data [20,21].

Other local factors may play a role in the detailed estimation of the performance of solar energy systems. Huld et al. [15], for instance, presented a method taking into account the influence of temperature. More frequently, however, typical efficiencies for the different solar system types are applied, following the state of the art [5,6], and determine whether the spatial constraints can be satisfied. Finally, economic factors can also be essential to determine the feasibility of a project, as shown again by Hoogwijk [5].

All in all, available databases and relevant restriction factors can be identified within a 2 dimensional matrix representing the global to the local scale as well as the theoretical to the economically feasible potential scale. All methods and data sources can be located somewhere in between (Fig. 2.2).

2.4. Challenges for the near future

A cross comparison of six databases for solar radiation estimates carried out by Suri et al. [11] showed that, in the case of yearly sum of global irradiation, the uncertainty, expressed by standard deviation, does not exceed 7% within 90% of the study regions for horizontal surfaces. Especially for mountain areas with their complex climate conditions, higher differences between the databases are expected. Therefore further improvements for complex terrains should be done.

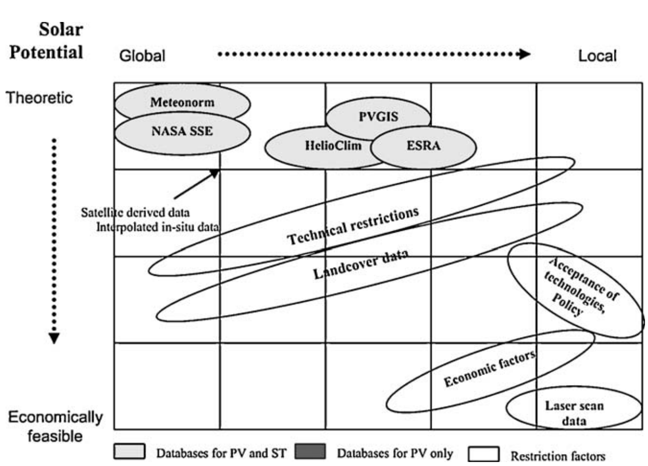

Fig. 2.2. Matrix of available databases and restricting factors covering the spatial dimension as well as the dimension of the top-down levels.

Compared with other renewable energy carriers like wind and biomass, solar energy can be also harvested in densely populated areas. Approaches and methods to derive an effectively exploitable potential are still in a process of evolution (e.g. laserscan data like LIDAR), but the opinions on what potential is really harvestable under sustainable conditions are quite diverse. Further improvements can be expected mainly in the explicit mapping of suitable rooftops regarding orientation and inclination, including also shadowing of neighbouring parts of buildings or trees. Especially the competition for installation areas between different solar system types (PV, solar heating) in case of decentralised usage have to be included in potential estimations, as the efficiencies of these systems differ substantially as well as the final energy use: electric energy can be returned to the grid, when not used; while thermal energy can be exploited only locally and with a limited storage capacity.

3. Wind resource potential

Wind was one of the first energy sources to be harnessed by early civilizations. Wind power has been used to propel sailboats and sail ships, to provide mechanical power for grinding grain in windmills and for pumping water. The world's first automatically operated wind turbine, which was built in Cleveland in 1888 by C.F. Brush, was 18 m tall and had a 12 kW turbine [22]. Nowadays the use of wind energy in electricity generation is widely spread and new units with nominal capacity of thousands of megawatts are being installed each year. The total wind power capacity installed worldwide has exceeded 120 GW in 2008 [23]. The ever increasing interest for wind energy, coupled with its uncertain nature, makes the estimation of wind energy perhaps the most difficult and crucial part of a project.

3.1. Identifying wind energy

As for solar power, the evaluation of the available wind energy follows a widely used top down approach. At the first level, the potential energy limited by all the physical geographical (high altitude areas, high slope areas), socio geographical (areas near towns, airports or archaeological sites, protected areas) and land use (areas used for agriculture, etc) constraints leads to the estimation of the theoretical energy.

This can be assessed at a scale of the order of few kilometers, simply by processing the available anemological data (long or short term), with either statistical models or interpolating techniques. The latter are used mainly when sufficient data are not available for the site of interest, but only for nearby ones. When the estimation scale needs to be much smaller, of the order of a few meters, the methods used must be more accurate (e.g. wind flow modelling techniques).

The theoretical energy can be further limited by the characteristics of the commercially available wind turbines (size, overall efficiency, full load hours) and the constraints of a wind farm.

Finally, the exploitable energy can be defined as the part of the theoretical energy that can be harvested using an economically feasible installation, given also the cost of alternative energy sources. The basic methods used to estimate the different categories of wind energy are presented in the next sections.

3.2. Estimating theoretical energy

3.2.1. Measurements – Data Collection

Every effort to estimate the theoretical energy of a region requires the availability of certain measurements, year-long or not,

referring to either the target site or another site nearby (reference site). According to Lalas [24], the available anemological data should include: (i) mean wind speed, on a monthly or seasonal basis, (ii) duration curves, (iii) persistence, i.e. continuous occurrence of wind speeds above a given speed, (iv) wind rose, i.e. joint frequency of occurrence of specific wind speed and direction, (v) power spectra of wind speed, and (vi) variation with height of most of the above. Ideally, in order to obtain an accurate assessment of the wind regime of an area, wind data measurements over a 10 year period are required [25]. However, Frandsen and Christensen [26] claim that a 1 year period of wind measurements may provide a reasonable indication of the potential for wind energy development, including a percentage of uncertainty from 5% to 15%, depending on the variability of the long term mean wind speed.

Using accurate inputs is crucial in wind resource assessment, so special emphasis should be given on the quality of anemological data. A detailed description of the various types of equipments, instruments, site specifications and other technical needs for wind energy assessment has been presented by Alawaji [27]. Meteorological towers are the most common means of assessing the wind resource at a location, typically between 40 and 60 m high, with cup anemometers and wind vanes positioned at multiple heights on the tower.

Nowadays, wind maps and global databases have been developed for many regions around the world, such as NCEP/NCAR and ECMWF databases, containing wind speed, temperature and pressure at several heights around the world [28]. However, low resolution of some existing data (i.e. hundreds of km) and lack of data for certain regions (i.e. offshore) have led to the development of new techniques. Ground based remote sensing instruments, such as SODAR, LIDAR or satellite, have started being used as alternatives to meteorological towers for wind resource assessment with high resolution. However, their effectiveness and efficiency will have to be proved since their possible limitations are still under examination.

Choisnard et al. [29] and Bruun Christiansen et al. [30] present a methodology for wind resource assessment using a series of satellite synthetic aperture radar (SAR) images, a technique particularly useful for regions where year-long time series are generally unavailable, such as offshore regions. Lackner et al. [31] investigate the use of an alternative monitoring strategy for wind resource assessment, the "round robin site assessment" method. Wind resource is measured at multiple sites within a year, using a single portable device and measurement time is distributed at each site over the whole year.

Data collected in any of the ways described above can then be processed in order to provide useful information about the wind energy. The following sections present the basic processing methods.

3.2.2. Statistical analysis

When year-long measurements for the target site are available, they usually constitute an enormous volume of data, difficult to analyse in its raw state. A simple solution would be to apply the proper statistical treatment in order to determine the probability density function (PDF) of the wind. The use of this frequency distribution approach can provide a simple method to evaluate the theoretical wind energy, because it provides useful information about wind speed.

Carta et al. [32] review and compare the most widely used and accepted distributions in the specialized literature on wind energy and the methods utilized to estimate their parameters. They conclude that the Weibull distribution has a number of advantages with respect to the other PDFs analysed. However, Weibull cannot describe all the wind regimes encountered in nature such as, for example, those with high percentages of null wind speeds, bimodal distributions, etc. Therefore, despite there are numerous examples in the literature of using the Weibull distribution for regional wind energy estimation, how to select the appropriate PDF for each wind regime in order to minimise estimation errors is still an open problem.

Stevens and Smulders [33] obtained the values of the Weibull distribution parameters using five different methods: moments, energy pattern factor, maximum likelihood, Weibull probability and the use of percentile estimators. The comparison of these analytical findings indicated that no significant discrepancies between the results from the different methods could be observed.

A Cumulative Semi Varigram (CSV) model has been derived by Sen and Sahin [34] to assess the regional patterns of wind energy along the western Aegean Sea coastal part of Turkey. This interesting technique provides clues about regional variations along any direction and yields the radius of influence for wind velocity and Weibull distribution parameters.

3.2.3. Forecasting techniques

When the available anemological data for the target site are insufficient, the measure–correlate–predict (MCP) methods can be used to estimate the theoretical wind energy. These algorithms can reconstruct the wind resource at target sites by using data from a nearby reference site. The idea is to correlate short term measurements at the target site with an overlapping long time series of the reference site using simple statistical models. According to Landberg et al. [28] climatological representativeness is obtained by having measurements for at least 5 but preferably 10 years.

The way the correlation is established between the wind speed at the two sites varies from method to method. A linear regression model is used in many cases, but other models are used as well. Rogers and Rogers [35] describe some of the MCP approaches in the literature and then compare the performance of four of these, using a common set of data from a variety of sites (complex terrain, coastal, offshore).

Addison et al. [36] state that conventional MCP techniques assume that the wind direction distribution at the target site is the same as that of the reference site, which may lead to a significant error and propose a correlation technique based on artificial neural networks (ANN). Bechrakis et al. [37] present a two site wind correlation model, also based on an ANN, in which concurrent measurements of a short time period for both sites are being processed.

3.2.4. Flow Modelling

The techniques described in the previous sections estimate the theoretical wind energy at a resolution of the order of few kilometers, in the best of cases, suitable for a raw evaluation of the wind potential of a region. However, when wind turbine installation is designed, the resolution should be of the order of few meters and hence wind flow models are employed.

Based on the theory of flow over small hills, some linearized flow models were the first to be developed for commercial use. In these models, the equations of motion were simplified by linearizing the advection terms and the other weaker nonlinearities in the turbulence closure equations [38]. Indicative examples of such models are the WAsP model [39], based on some linearized forms of the fluid flow equations, and the MS Micro model [40].

A significant application is Wind Atlas methodology [39], a method of vertical and horizontal extrapolation away from measurements taken somewhere within or near a target site, using steady state flow solutions (Fig. 3.1). The method directly corrects existing long term measurements and estimates the generalized wind climate, the hypothetical wind climate for an

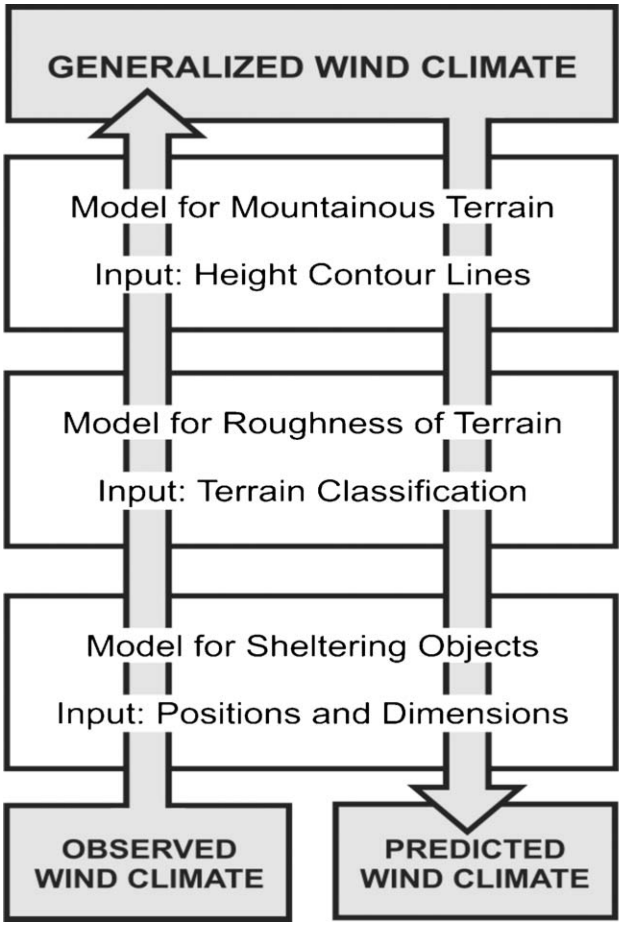

Fig. 3.1. Wind atlas methodology. Adapted from [39]

ideal, featureless and completely flat terrain with a uniform surface roughness, assuming the same overall atmospheric conditions as those of the measuring position. This method can also be used in reverse, in order to determine to a high accuracy the specific winds at a site. This methodology, combined with WAsP, has been applied in a large number of countries (all of EU countries, Russia, Northern Africa), because of the modest computer resources requirements has become a de facto standard for the wind industry [41].

The main disadvantage of linear models is the low accuracy in the calculations of wind conditions in steep/complex terrain with known overestimates of the hill top acceleration and underestimates of the lee side decelerations [38]. Another problem is that thermally driven winds are not modelled in a satisfactory way, especially with the Wind Atlas Methodology [28].

These limitations are becoming significant, since the pressure for increased wind capacity is leading to the installation of wind farms even in areas of increased terrain complexity. In such cases, more complex nonlinear models permit overcoming many of the shortcomings mentioned above, and also provide a more accurate representation of the case under consideration. The most popular nonlinear model is RaptorNL, a computational flow model that simulates turbulent flow over topography.

Palma et al. [42] evaluate the theoretical wind energy of a coastal region using a wide variety of techniques, including field measurements and computer simulations using linear and nonlinear mathematical models and compare the results.

3.2.5. Mesoscale modelling

A different type of models, which began to emerge as a major focus of research during the late 1990s, are atmospheric mesoscale models. They were developed for general weather prediction at fine resolution (1–10 km) and in particular for air pollution studies, and aviation purposes. They can be applied to estimate the wind resource of a region, by solving numerical equations for the conservation of momentum, heat and moisture, together with a continuity equation.

Lyons and Bell [43] used a numerical mesoscale model to describe the variation of wind energy across a coastal plain of Western Australia and to compare the results with those of a simpler linear flow model. Katsoulis and Metaxas [44] use a mass consistent numerical mesoscale model to estimate the theoretical wind energy in Corfu, Greece, comparing the results with the statistical analysis of wind data from local meteorological stations. The major problem of mesoscale modelling is that resolutions of 1 km or less require a very high computational effort.

3.2.6. Combination of models

A way to overcome this problem is the use of mesoscale models in combination with a wind flow model (microscale model). Instead of trying to resolve all small scale terrain features, the mesoscale modelling stops at a resolution of approximately 5 km and local predictions are made with a wind flow model (Fig. 3.2).

Frank and Landberg [45] use the Karlsruhe Atmospheric Mesoscale Model, combined with the linear wind flow model WAsP, to estimate the theoretical wind energy of Ireland. Brower et al. [46] develop MesoMap, a combination of MASS mesoscale atmospheric model and microscale model WindMap, and apply it for the estimation of theoretical energy in several areas in USA. Pepper and Wang [47] use the PSU/NCAR fifth generation Mesoscale Model (MM5) in conjunction with an h-adaptive finite element model in order to conduct wind energy assessment in central Nevada. Kondo et al. [48] use a mesoscale model (AIST-MM) combined with a multi layer canopy model to estimate wind energy in an urban area.

3.3. Estimating exploitable energy

There is no definite methodology referring to the estimation of exploitable energy. Hence, certain indicative examples of its estimation will be mentioned, at various scales, regional, national or even global. Voivontas et al. [49] attempt to estimate the theoretical and exploitable wind energy in a Greek island, using a GIS Decision Support System (DSS). Acker et al. [50] use GIS and wind maps, created by a mesoscale wind energy model, to produce a wind resource inventory in the state of Arizona, to evaluate the most promising sites for wind development and to present the cost of energy by using the NREL wind energy finance calculator. Hoogwijk et al. [51] present the assessment of the global theoretical and exploitable wind energy, performing a sensitivity analysis for uncertain assumptions. de Vries et al. [52] investigate the potential of wind, solar and biomass, focusing on uncertainties in land use cover, by building four different scenarios. Biberacher

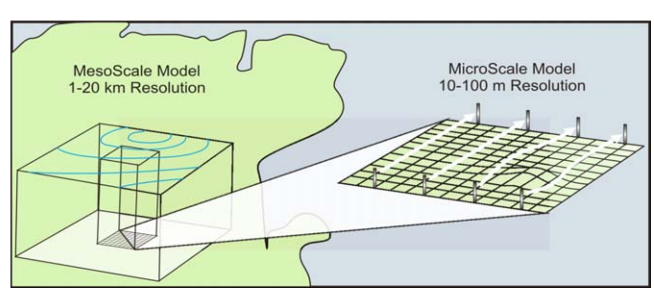

Fig. 3.2. Downscaling using mesoscale and microscale modelling. Adapted from [169]

et al. [3] developed a global GEOdatabase, including all renewable energy resources, at high resolution taking into account competitive land uses.

3.4. Challenges for the near future

According to Petersen [53], a point has been reached where by giving the coordinates at any spot on Earth, the local wind energy can be estimated with a reasonably well known uncertainty. This has been made possible due to model development, where linear wind flow models are combined with adapted nonlinear models and mesoscale meteorological models, to fully exploit the capabilities of each method.

The greatest challenge for wind resource estimation is to find flow models and numerical schemes which can pick up the main features of the wind flow in complex terrain and/or very complex climatology while keeping the calculation effort at an acceptable level. Other challenges are related to the prediction of the turbulence conditions and extreme winds at specific sites and the reduction of the uncertainties in the estimates. Ayotte [38] presents the most recent developments and the challenges which still exist in flow modelling for wind resource assessment.

With respect to the huge potential of planned offshore farms, research attention has shifted to the estimation of the offshore wind potential. Many papers have been written on this subject in the last years [54–56]. The question that needs to be answered is whether the methodologies mentioned above can still be satisfactorily used for this purpose, given the unique features of these cases (strong thermally driven wind flow, sea surface roughness, bathymetry). Finally, recent studies have been initiated to consider the effect of climate change on the wind potential energy [53].

4. Wave energy potential

The worldwide wave energy potential is estimated of the same order of magnitude as the world electrical energy consumption, however power generation is not currently a widely employed commercial technology. Some of the earliest recorded attempts to convert wave energy into more usable forms date back to several centuries, and today, thanks to the offshore oil industry and offshore wind energy development, much of the infrastructure and knowledge necessary to efficiently generate energy from the ocean already exists. Several wave energy conversion devices have already demonstrated the potential for commercially viable electricity generation and are expecting pre-commercial deployment in Europe. However, in order to achieve competitiveness, a good understanding of wave climate at the installation site and weather forecasting techniques are necessary.

4.1. Identifying wave energy potential

As already pointed out, wave energy can be considered as a concentrated form of solar energy. The differential heating of the earth generates winds which transfer some of their energy to form waves as they pass over open bodies of water. Waves travel great distances without significant losses and so act as an efficient energy transport mechanism across thousands of kilometers.

Whatever the means used to record or predict a wave climate, the sea state is usually described by using a simplifying set of statistical parameters. A sea state can then be represented as a spectrum of regular waves and often summarized in terms of wave height spectral peak, dominant wave period and mean wave direction. These wave spectral parameters are then used to quantify the wave energy resource and to estimate the flux of energy per unit of wave crest. The variation in sea states over a period of time can be represented by a wave scatter diagram, which indicates how often a sea state with a particular combination of wave height and period occurs. The angular distribution of wave power is usually represented in a "wave rose". Synthesizing, the statistical parameters used are very similar to those adopted for wind energy.

Wave energy is a renewable resource and therefore it is virtually inexhaustible in duration but limited, and also highly variable, in the amount that is available per unit of time. The theoretical potential identifies the physical upper limit of wave energy available at a certain site. The technical potential takes into account restrictions regarding the state of the art of the technology, limiting the theoretical potential and reducing the area that is realistically available for energy generation. The potential is further reduced when additional but compulsory restrictions are taken into account such as the proportion that can be utilised respecting ecological and socioeconomic factors. The methods used to estimate these potentials, along with several examples found in the bibliography, are described in the following sections.

The World Energy Council has estimated the worldwide wave power resource in deep water between 1 and 10 TW [57]. As most forms of renewables, wave energy is unevenly distributed over the globe, varying by location and time. The best wave climates in terms of increased wave activity, with annual average power levels between 20 and 70 kW/m of wave front, are found in the temperate zones (30–60° latitude). However, attractive wave climates are also found within equatorial zones (0–30° latitude) where regular trade winds blow and the lower power levels are compensated by the smaller wave power variability.

Although the scale and character of the wave energy resource in many regions around the world remain poorly understood and ill defined, especially in nearshore areas, several efforts have been made to estimate the wave energy potential at regional, national and global scale. Some of them are described next, grouped according to the methods used and to the sources of data.

4.1.1. Direct and remote measurements

The most realistic wave data is collected in situ using moored buoys, fixed structures (laser and acoustic sensors) and bottom mounted pressure and acoustic sensors. The most common system is buoys. In the past, they could only measure wave energy but in the last years buoys equipped to measure horizontal surge and sway motions are used, allowing the calculation of wave directionality. Some wave recording buoys have been collecting data for years, gathering useful long term series.

However, these types of measuring systems are not widely available and do not have a worldwide evenly distributed cover, mainly due to high costs and difficulty related to harsh environment.

Satellite technology has started being used for accurate recording of wave height, velocity and direction, including both local and localised effects. It is not sensitive to bad weather conditions, but has low frequency of measurements and relatively high distance between tracks as drawbacks. Krogstad and Barstow [58] describe the methodology used to calculate wave height, wind speed and wave period over 15 years based on satellite data. They present several case studies and also provide a few Internet sites where satellite wave data can be found. Barstow et al. [59] used two years of altimeter data to construct a global map of the available wave energy resources in deep water. Despite the relatively short record length, the analysis succeeded in generating reasonable estimates of the spatial variation of mean wave energy.

Satellite observations are able to provide reliable global long term wave statistics, also contributing to improve short term wave predictions. Combined with short term forecasting techniques, these data could be used to modify controlled response for safety in approaching storms and to call for dispatch balancing plant in the

electricity network to accommodate reductions in wave energy production.

4.2. Statistical analysis and numerical models

Measuring systems produce a huge quantity of data that could be difficult to evaluate in its raw state. In order to help in the hindcasting and forecasting of wave climate, a more or less complicated statistical analysis is generally applied. Regarding the hindcasting of wave climate from meteorological data, Smith et al. [60] proposes a new statistic that measures the rate of change in the wave period from one wave to the next, which would be relevant to wave energy devices. Statistical analysis could also help to determine the long term resource potential for a given site. This can be used to evaluate a site for development viability, but will not work for predicting the energy produced.

According to Rusu and Guedes Soares [61], wave energy can be accurately predicted within a window of a few days not by statistical analysis, but by using numerical models, the most widely used of which are WAM (Wave Analysis Model), WAVEWATCH III, FUNWAVE and SWAM (Simulating Waves Nearshore Model). They model wave generation based on wind-wave models, wave propagation and transformation, from open ocean to within ports and harbors. While WAN, WWIII and FUNWAVE are used at global scale for offshore locations, linking meteorological parameters to production of ocean wave regimes, SWAN is used to introduce the wave transformations that occur near the coast (whitecapping, bottom friction and depth induced wave breaking) [62].

Several authors have reported detailed energy resource assessments for particular regions or countries: Ireland [63], United Kingdom [64], Portugal [65], California [66], Canada [67], the Baltic Sea [68]. These types of studies involve analysis of wave data from buoys, satellites, numerical wave hindcasts or a combination of these sources.

4.3. Estimating technical potential

Wave power estimates usually describe the energy flux due to wave propagation but only a fraction of the energy flux available at any site can be captured and converted into more useful forms of energy. This fraction is imposed by the wave energy converter (WEC) inherent power limitation. How to calculate the fraction of "extractable" resource is not yet well established since there is not an agreement on the optimum wave energy conversion mechanism.

It is also necessary to consider the effect of the resource variability on device performance since the excess wave power in sea states larger than a threshold power level is unexploitable. This threshold will depend on device/wave farm hydrodynamics, but in the case study presented by Folley and Whittaker [62] four times the average incident wave power has been used. They present a method to estimate the wave energy resource in nearshore areas, proposing a measure of the resource that represents more accurately the potential for exploitation, avoiding omnidirectional wave energy and discounting high energy sea states.

Boehme et al. [69] suggest some figures of the loss in electricity production (and therefore, the reduction of theoretical resource to the extractable potential) generated with a Pelamis type device in Scotland.

4.4. Estimating economic and sustainable potential

Most of the examples found in the literature agree on the restrictions that must be considered in order to estimate the realisable wave energy potential and how to rank feasible locations for wave energy deployment. Some suggest how the costs could be reduced, and several defend GIS as an appropriate tool to jointly evaluate the social, economic and environmental constrains. For instance, Henfridsson et al. [68] examines possible examples of power installations in the Baltic Sea. Activities such as commercial fishing, shipping channels, areas of military interest, sites of marine archaeological importance and valuable biological reserves were taken into account in the definition of the feasible areas. Also geographical conditions were considered, such as distances from land and grid, the depths and substrate of the seabed, which can set boundaries to what is economically feasible.

In the case of Boehme et al. [69], GIS technology was used as the computer environment within which renewable resources, along with most of the physical constraints on their development, were mapped. The GIS program was also used to model renewable electricity generation, establishing the spatial relationships between resource, generation and electrical load datasets.

The method presented in Nobre et al. [70] constitutes a reference example in performing geo-spatial analysis aiming to identify the best location to implement a wave energy farm off Portugal coast. Several factors, such as technological limitations, environmental conditions, administrative and logistic conditions, are taken into account. Some restrictions are imposed in the analysis (exclusion zones) while other areas have their suitability ranked with weighting factors. The result is a spatial suitability index for farm deployment.

The cost involved in transmitting power to the electricity network from an offshore location is clearly more expensive than from an onshore location, due to the underwater cable infrastructure. Prest et al. [71] describe a method, based on GIS, which optimises the cable route between a wave farm and the electricity network, while taking a range of exclusion zones. Graham et al. [72] also use techniques available through GIS to optimise the integration of marine energy into the electricity network.

4.5. Challenges for the near future

For most wave energy conversion mechanisms, it is necessary to tune the oscillating bodies to some period of the waves. Hence, a good understanding of the wave climate at the site is required. A better resource analysis and weather forecasting is one of the most important challenges faced by marine renewable resources [73] in order to achieve competitiveness. It is also important to produce good and reliable information on the steadiness of the wave energy resource throughout the year and on the severity of the wave climate extremes when conducting resource assessments for wave energy projects, since production and survival of converters will rely on them.

It will be critically important to ensure that the development of new ocean energy technologies do not harm the marine environment, taking into account all the environmental restrictions that would assure the sustainability of its exploitation, while the resource assessment is performed. Recent studies have also suggested the necessity of considering, in long term planning, the impact that climate change could have on the marine resources [74].

5. Dry biomass and energy crops potential

Biomass resources have been largely used as traditional fuels and are now being promoted as a strategy to achieve sustainable development. Biomass is mainly available locally, allows the widespread production of energy at reasonable costs and can help to mitigate climate change, develop rural economies and increase energy security. Consequently, several methods and tools have been developed to assess the availability of biomass resources. We focus in this section on methods and tools for biomass estimation at the regional level subdivided by biomass type.

Biomass is defined as the biodegradable fraction of products, wastes and residues from agriculture, forestry and related industries, as well as the biodegradable fraction of industrial and municipal wastes. Moreover biomass can be grown on purpose in dedicated energy crops. Residual biomasses derive from:

- the agricultural sector, both in the form of crop residues and of animal waste;
- the forestry sector, from forests' thinning and maintenance;
- the industrial sector of wood manufacture and food industries;
- the waste sector, in the form of residues of parks maintenance and of municipal biodegradable wastes.

Biomass potentials are classified depending on their theoretical, techno-economical and sustainable availability. The theoretically biomass potential can be estimated on the basis of biophysical and agro-ecological factors that determined the biomass growth and extension and the residues production ratios. The techno-economical potential is then estimated taking into account accessibility, resources competition, biomass logistics, production costs and all other factors that constraint the theoretical potential. Sustainable potential is a further assessment that aims at evaluating the amount of biomass that can be obtained considering socio-economical and ecological impacts of this type of energy projects. Constraints may vary according to regional specificities such as forestry, agricultural and industry practices, to socio-economic conditions and to the natural environment.

We will first consider dry biomass, namely that with a humidity content below 30%, and analyse specific methods to estimate the potential of different sources, namely, woody biomass, agricultural biomass, energy crops and industrial residues.

5.1. Estimation of biomass potential

5.1.1. Woody biomass

Woody biomass estimation methods are usually based on forest inventories and agricultural censuses. The theoretical potential of biomass in forests is typically estimated through biomass allometric regression equations (BARE) and biomass expansion factors (BEF) [75]. Allometric equations are regressions that relate diameter and height of a tree to stand volume and total biomass volume [76]. A vast bibliography is available presenting allometric equations (e.g. [77,78]). Local and regional characteristics such as climatic variables and topography have a strong influence in forest growth and so in the aboveground biomass volume. Specific allometric equations should be developed for each tree species, for each forest development stage and for each region. As these values have not been computed for all interesting species and locations, many authors adjust equations available in literature.

BEFs are used for total aboveground biomass estimations and their components as an intermediate step for carbon stock and change calculation in forests. BEFs convert timber volumes to whole tree biomass and are calculated as the ratio between aboveground biomass and stem volume [79]. Some controversies have arisen regarding BEFs use for biomass estimations such as its inapplicability to trees below merchantable wood [80], and BEF statistical error is often unknown leading to biased estimates. Efforts are being done to obtain more accurate BEF [81] including the differentiation by age and the estimation of error, but they cannot be applied when stand development conditions deviate from those under which the BEFs were computed [82].

Forest treatments, mainly pruning, thinning, and final felling are a key element as annual forestry residues production depends on these factors. Esteban Pascual [83], Panichelli and Gnansounou [84], Panichelli and Gnansounou [85] give examples of biomass estimations based on forest management practices.

The main uncertainty in estimating woody biomass potential is the difficulty to account for forest dynamics. The last century has seen the development of various models for this purpose. Such models have been developed following different approaches and vary from complex eco-physiological models, suitable for the study of the impact of forest on climate change, to empirical models. Forest growth models generally can be classified within the following categories [86,87]: (a) highly aggregate volume over age models, used for regional yield forecasting; (b) stand models, used to predict the growth as a function of age; (c) size class models, used to predict the plants growth in terms of variations of the diameter distribution; (d) individual tree models that provide information about the plant growth, on the basis of spatial relations. Some models of forest growth [88] dynamics have been developed but not fully integrated in biomass potential estimations. One of these is CO2FIX [89,90] that has been designed to estimate all carbon flows from the atmosphere to the standing biomass, from biomass to decay in the soil, from the soil back to the atmosphere. These flows describe, through many parameters, the natural dynamic of a forest. Moreover, flows can be added to account for forest management (cuttings and crop rotations) and for the use of the woody products.

5.1.2. Agricultural biomass

The theoretical potential of crop residues can be estimated on the basis of the cultivated area or the agricultural production for each crop (usually available from regional or national statistical offices) and average product to residue ratios or residue yields derived from literature or from referenced local trials. Different authors have proposed product to residue ratios [91]. This method has been widely applied to estimate agricultural residues availability for energy purposes [92,93]. The residue availability may significantly vary with local agricultural practices and climatic conditions. Product to residue ratios should thus be estimated at regional level on the basis of field trials [94].

The theoretical potential of agricultural residues for energy purposes is restricted by competition and logistics constraints. Almost half of the total agricultural residues are exploited in non-energy applications [95]. Moreover, agricultural machineries are not able to collect all the residues from the soil and typically leave 40–50% of it on the field [96].

Moreover, crop residues play an important role both protecting soil from erosion and returning nutrients to the soil. Residues removal should be evaluated in each specific case, according to local soil and climatic characteristics and to agricultural practices. In the USA this a very important issue given the high soil erosion rates experienced in the central plains, where wind, water availability and soil conditions strongly affect the amount of residue removal, as modelled by Graham et al. [97]. Agricultural residues have to be collected and transported to the conversion plant. Since the bulk density of agricultural residues is generally low, transport costs can be significant and need to be carefully assessed. One way to contain transportation costs is to process residues and densify them, for instance by baling.

5.1.3. Energy crops

Biomass can be supplied by dedicated agricultural crops of arboreous and herbaceous species: short rotation forestry (SRF, e.g. poplars, willows, eucalyptus), annual crops (e.g. corn, soy, sugar cane, sorghum) and perennial grasses (e.g. switchgrass, miscanthus). Several models have been developed to support the decision over which species to grow. Local climate, morphology, soil characteristics, water and nutrients needs are commonly used to identify the set of species suitable for a specific area [98]. For example, potential biomass productivity of tree species can be assessed on the basis of the FAO/IIASA Agro Ecological Zones

approach [99], while some information for herbaceous species can be found in the ECOCROP database (ecocrop.fao.org/).

Eventually, the most important issue regarding energy crops is the assessment of available land. Some models have presented assessments of land availability at global level [100]. However, once at regional scale different methods are needed in order to account for local socio-economic and environmental conditions. Land available for energy crops can be identified with the help of current land use data and statistical databases. However, land conversion costs, social concerns and environmental constraints may limit the amount of available land for energy crops. Given a set of species suitable for a given area, an optimization problem of the entire energy chain (including cultivation and transport) must be solved in order to determine the amount of land to be dedicated to each specific crop [101].

A different approach for estimating energy crops potential is the economic modelling of the entire agricultural sector. Economic models account for biomass production for the internal market, exports and imports, and detailed costs and benefits of the major farming goods. The Polysis model [102], developed for the USA estimates biomass production on the basis of the net profits compared with those derived from conventional crops. This model relies on many assumptions that range from farming practices to macro-economic variables of the agricultural sector.

GIS based applications allows considering spatial patterns of biomass distribution. Graham et al. [103], Graham et al. [104] developed a regional scale GIS based modelling system for evaluating potential biomass production and costs from energy crops.

5.1.4. Industrial residues

Biomass from industrial residues includes wood from sawmills and timber mills and by products of the food industry. The principle of waste reduction, re use, recycle and recover should be considered also when proposing waste to energy projects.

Municipal solid waste, liquid by-products from the pulp and paper production industry; food processing wastes can all be used for energy conversion, in some cases together with the wet biomass, as discussed in the next chapter.

The availability of information on quantities of current biowaste production may significantly differ across the waste streams. Municipal solid wastes are monitored by government, so that statistics about their availability and the type of waste should be easily recovered from the national statistical offices. Similarly, the industry and service sectors are normally required to notify the type and the amount of waste produced, according to the categories of waste.

Solid industrial residues consist mainly of clean wood fractions from the secondary wood processing industry. These residues are already concentrated at a processing industry and are often already dried, which reduces logistic and pre-treatment costs. However, wood industries already use part of these residues for heating purposes, so that the final amount of wood residues available for other energy conversions is reduced. Wood industrial wastes can be estimated from the quantity and quality of wood processed and from the type of process that the wood undergoes. The actual quantity of residues depends on several factors, such as wood properties, type of operation and maintenance of the plant. Again, alternative uses of wood residues, such as chips for pulp production, raw materials for particleboard and fibreboard production, must also be considered (Fig 5.1).

5.2. Spatial patterns and optimization

State of the art in biomass to energy planning is focused on GIS based approaches where biomass potential is estimated from geo-references inventory data. Once that the available potential of biomass is assessed, the system is optimized based on cost minimization of biomass production and utilization in energy conversion facilities.

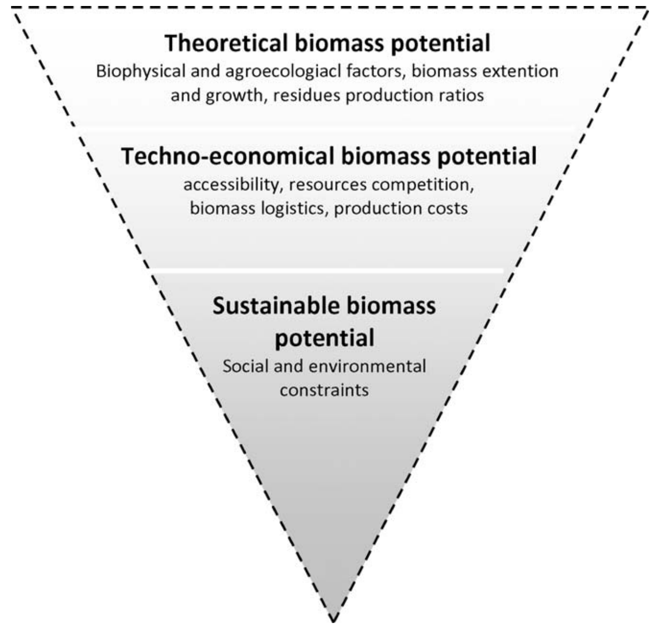

Fig. 5.1. Classification of biomass potentials.

Satellite images have been widely used to assess spatial patterns of biomass production. Methods account for the integration of forest inventories with satellite imagery [105,106], the use of LIDAR remote sensing data [107], teledetection applications [108] and normalized difference vegetation index (NDVI) data processing [109].

One of the main issues is the distance of the conversion plant from the needed feedstock and the capacity of the plant itself. Given a certain biomass availability and regional distribution, at the increase of size, in fact, collecting distances increases and thus also the biomass supply costs [110–112]. Many models have evaluated these issues, among them the Biomass Resources Assessment Version One (BRAVO) system in a computer based DSS to assist the Tennessee Valley Authority in estimating the supply cost for wood fuel as a function of the hauling distances [113]. In this type of analysis, spatial information is needed in order to know where to collect the biomass from and where to deliver it.

Interactions of biomass supply and demand have also been a major subject of research. Masera et al. [114] have assessed the wood fuels resources in Mexico, Slovenia and Senegal using the Woodfuel Integrated Supply/Demand Overview Mapping model (WISDOM). The model is a GIS based tool aiming to analyse firewood demand and supply spatial patterns highlighting areas in which several criteria of interest coincide.

Much of the present work is directed toward the development of GIS based decision support tools of the complete biomass-to-energy chain, such as that developed by Frombo et al. [115], Frombo et al. [116]. Another GIS based model for public forests, based on inventory data, was developed and tested in the Northern Black Forest region, Germany [117]. The feasibility of the biomass to energy chain was assessed in the Tuscany region [118]. Tatsiopoulos and Tolis [119] have evaluated the economic aspects of the cotton stalk biomass logistics in a mathematical formulation for Thessally, Greece. Centralized and decentralized approaches were considered and the entire model was driven by a GIS interface that permitted to define the suitable location for siting power units. These tools are useful to identify the main parameters that

affect location and number of bioenergy conversion facilities based on plant capacity and spatial distribution of the available biomass resources.

DSSs may also allow policy makers to assess the impact of bioenergy policies: Chalmers et al. [120], for instance, have created a GIS based tool that estimates the effect of policy constraints in thinning.

Finally, they may explicitly include economic considerations. Kinoshita et al. [121] have focused on the spatial modelling of forest biomass as a function of production costs for different machinery and forest treatment. An integrated GIS based approach including techno-economical, socio-political and environmental constraints to biomass production and utilization was developed by Perpiñá et al. [122] to evaluate biomass to energy potential in the Valencia Community, Spain. Panichelli and Gnansounou [84], Panichelli and Gnansounou [85] have tackled the problem of resources competition between energy facilities and farm gate price variability in function of biophysical and location constraints. The DSS model was applied in Northern Spain to determine optimal locations for bioenergy facilities.

5.3. Challenges for the near future

The main challenges in biomass to energy planning deal with the improvement of models to account for forest and agricultural dynamics and their integration into GIS environments, the development of specific biomass estimation factors and equations, the assessment of biomass competition between energy conversion and other uses, and the development of multicriteria optimization models. Moreover, social and environmental considerations [123] need to be taken into account in order to face issues such as biodiversity loss.

6. Wet biomasses and biogas potential

In this section of the paper, we will analyse biogas production *via* anaerobic digestion (*AD*). Biogas produced via AD is a mixture of methane (CH_4) and carbon dioxide (CO_2), in a ratio of about 60/40 to 70/30. Biogas can then be burned in stationary engines to produce electrical and/or thermal energy or to fuel vehicles.

In recent years, AD has been developing as one of the most attractive renewable energy resources especially in Northern Europe. European production of primary energy from biogas has reached 5.9 million tons of oil equivalent (Mtoe), increasing by 20% since 2006 [124]. Biogas derives from landfills (49%), waste treatment plants (15%) and agricultural units (36%). Gross electricity production from biogas in the EU was about 17 TWh in 2006; more than half is produced in cogeneration plants [124].

Biogas can be produced from nearly all kind of biological feedstock types. The largest resource is represented by animal manure, slurries, and organic waste streams. Dedicated agricultural crops and crop residues are also promising feedstock such as grasses (e.g. straws from wheat, rice, and sorghum) or silage maize.

The increasing interest in animal manures and slurries is due to the many co-benefits that derive from their energy exploitation. When untreated or poorly managed, animal manure becomes a major source of air and water pollution. Nutrient leaching, mainly nitrogen and phosphorous, ammonia evaporation and pathogen contamination are some of the major threats. Moreover, from the climate change perspective, the animal production sector is responsible for 18% of the overall greenhouse gases emissions in CO_2 equivalent [125]. The energy use of manure contributes to decrease water, soil and air pollution, while pathogens population possibly present in the manure are reduced [126]. Moreover, the digestate, the final residue of AD, can be used as soil amendment, for fertigation or as a colloidal humus [127,128].

The potential energy from biogas can be assessed following these steps: first, feedstock should be assessed at local level on the basis of the socio-economic and farming conditions, which can significantly vary with country legislation and common agricultural practices; this assessment should take into account technical (feedstock suitable to be used as AD substrate) and socio-economic (feedstock that can economically be treated in AD and that are not subtracted to other end uses) constraints. Second, on the basis of available substrates, the conversion technology should be chosen and the energy system designed: socio-economic (e.g. local energy demand) and geographical (e.g. land morphology, road network) constraints should thus be considered.

6.1. Feedstock

Even though the chemical and physical characteristics of biomasses are extremely variable (for substrates characteristics see, e.g. [129,130]), a wide variety of high moisture content biomasses can be used as substrates for biochemical conversions such as AD. In this section we will focus on animal manure, while dedicated energy crops were discussed in Section 5.1.3.

Typically, more than one substrate is simultaneously fed to the digester in order to improve the methane content in biogas. This practice is commonly known as co-digestion. The most common co-digestion application can be found in agricultural biogas plants where manures are co-digested with smaller amounts of grasses, crop residues, maize or grass silage. In fact, co-digestion of manure with biomass is a way to adjust the C:N ratio, which is lower for manure and higher for grasses and residues [129,131,132].

Biogas yields vary depending on the kind of raw material used as substrate, given the same conversion technology. This is due to the different chemical and physical composition of the raw material and, in particular, to the difference of organic matter, carbohydrate and fat content. High fat content, for example, provides biogas with high methane content. In addition, the composition of a specific raw material can vary markedly among sites or with time. For instance, the time of harvesting will affect the content of various carbohydrates in ley crops, and thus affect the degradability of the crop itself. The methane potential varies with different livestock: species, breed, growth stage of the animals, feed, amount, and type of bedding and also any degradation processes which may take place during storage are all factors that affect methane potential [133].

Modelling techniques are used to optimise the spreading of animal manure on agriculture land. The USDA model developed for Chesapeake Bay [134] is a nonlinear mathematical programming model that estimates manure land application costs from the distribution of manure, given farming practices in use, and from the land available for manure spreading. The model is based on the interaction between geographical information and numerical databases, derived from the agricultural census.

The literature proposes different methods to evaluate biomass availability. The assessment of suitable feedstock is at the basis of analysis of biogas contribution to the energy balance of a region (e.g. Salomon and Silva Lora [135] for Brazil; Jingura and Matengaifa [136] for Zimbabwe). The assessment of the energy potential should start from the analysis of territory configuration (digital cartography) as well as agricultural and industrial censuses and current farming practices. This information allows estimating the amount of different types of feedstock available in each portion of the territory. The integration of GIS with statistical data stands at the base of several models, such as that developed by Batzias et al. [137] to estimate the regional distribution of biogas potential in Greece.

The amount of raw material available can also be estimated from specific dataset on socio-economic (as for wastes) and

Table 6.1
Parameter used to assess the availability of biomass from zootechnical residues (dry kilogram per head per day).

Livestock	Residue	Washington State, US [170]	Greece [137]
Dairy milker	Manure	6.55	4.22
Dairy calve	Manure	1.83	–
Cattle	Manure	2.76	–
Calve	Manure	0.69	–
Swine	Manure	0.45	0.59
Horse	Manure	5.5	7.12
Poultry egg layer		0.27	0.03
Poultry broiler		0.18	–

farming (as for manure residues and energy crops) activities. For example the amount of animal manure can be estimated from the number of animal units in an area multiplied by specific parameters (e.g. Table 6.1) that returns the potential biomass supply and its organic content. The number of animal units is commonly given by national agricultural surveys (or Eurostat for all the European countries).

In general, the amount of biogas generated by any type of feedstock can be calculated by multiplying the amount of input feedstock; its availability factor; the percentage of dry matter; the percentage of organic content per dry matter; and the gas generation rate per unit of substrate. Examples of dry matter and organic matter content for various substrates are listed in Table 6.2.

The availability fraction strongly depends on current farming and disposal practices; e.g. for Greece it was estimated at 0.45 for cattle manure and 0.80 for pig manure [137]. The expected amount of energy from biogas is then obtained by multiplying the amount of biogas times the percentage of methane and its lower heating value (typically 34.6 GJ/m^3).

Feedstock that can be used as substrates share the common characteristics of biomass: they are largely available, originate from different sectors and are disperse over the territory. Thus, an effort is needed to collect and deliver the feedstock to the plant. The AD process can be carried out at a large variety of plant scale (from few kWe to several MWe). However, as the scale increase, one has to contrast the increasing cost of feedstock collection vs. economies of scales. This issue has been explored for AD [138] and for lignocellulosic biomass and thermo-chemical combustion conversions [139]. The characteristics of wet biomasses (high water content, composition, odour) make transportation difficult and expensive. For example, transportation accounted for 35–50% of the total operating costs in the Danish centralised biogas plants [140]. To reduce costs and favour bigger centralised digesters, manure transportation in pipelines is considered a valid alternative to trucks in intensive farming areas [141,142].

6.2. Challenges for the near future

Modelling techniques in this field are typically used to optimise the management of animal manure. Besides the Chesapeake Bay model already mentioned, other models and DSSs have been developed, always with the aim of optimising manure spreading on cropland (e.g. [143]). The use of manure as an AD substrate used either alone or with other biomasses represents a relative new way of managing manure. Models are thus needed to evaluate all the consequences of this practice and to integrate it in the overall management of a farming system. These models should always be based on the interaction between geographical (data on cropland cover or other spatially explicit features) and numerical databases (such as the agricultural censuses that collect information on animals).

7. Geothermal energy resource potential

Geothermal energy is the heat that can, or could, be extracted from the interior of the Earth. This heat has two primary sources: the decay of the long live radioactive isotopes and the stored energy from planetary accretion. Geothermal heat has the advantage of being available all day and in all seasons.

Geothermal energy, as natural steam and hot water, has been exploited for decades to generate electricity, in domestic heating and industrial processes. In year 2000, geothermal resources have been identified in over 80 countries and there are quantified records of geothermal utilization in 58 countries in the world [144].

7.1. Classification, definition and uses of geothermal resources

As opposed to other sources or energy, renewable or exhaustible, there is not an agreement on the definition and classification of geothermal resources. According to Muffler and Cataldi [145], the accessible resource base corresponds to all of the thermal energy stored between the Earth's surface and a specified depth in the crust, beneath a specified area and measured from local mean annual temperature. The accessible resource base includes the useful accessible resource, which could be considered as resource, constituted by the part that could be extracted

Table 6.2
Characteristics of few selected feedstocks [171].

	Dry matter (dm) content (%)	Organic matter (om) content (% dm)	N_{tot} (% dm)	P_2O_5 (% dm)	K_2O (% dm)	C/N	CH_4 yield (N dm^3/kg om)
Liquid cattle manure	6–11	68–85	2.6–6.7	0.5–3.3	5.5–10	10–17	260
Solid cattle manure	11–25	65–85	1.1–3.4	1.0–1.5	2–5	14–25	300
Liquid hog manure	2.5–9.7	60–85	6–18	2–10	3.0–7.5	5–10	450
Solid hog manure	20–25	75–90	2.6–5.2	2.3–2.8	2.5–3	9–16	450
Liquid poultry manure	10–29	75–77	2.3–6.0	2.3–6.2	1.2–3.5	–	400
Solid poultry manure	32.0–32.5	70–80	5.4	–	–	–	400
Grass silage	26–82	67–98	3.5–6.9	0.38–0.76	–	–	500
Corn Stover	86	72	1.2	0.5	1.7	30	700
Straw	85–90	85–89	0.5	0.2–0.4	1.0–2.3	70–165	600
Miscanthus	–	–	–	–	–	–	495
Apple waste and peel	2.0–3.7	94–95	–	0.73	–	6	330
Potato waste and peel	12–15	90	5–13	0.9	6.4	3–9	250
Fruit wastes	40–50	30–93	1.0–1.2	0.5–0.6	1.2–1.6	30–50	400
Mixed vegetable waste	5–20	76–90	3–5	0.8	1.1	15	400
Yard waste	11.7	87–93	3.3–4.3	0.3–2	2–9	12–27	600
Municipal organic waste	9–37	74–98	0.6–5.0	0.3–1.5	0.3–1.2	15–21	700

economically and legally at some specified time in the future (less than a hundred years). Fig. 7.1, taken from Muffler and Cataldi [145], illustrates in graphic form these and other terms that may be used within the context of geothermal resource assessment.

There is another common criterion based on the enthalpy of the geothermal fluids. The enthalpy could be considered almost proportional to temperature, so the resources are divided into low, medium and high enthalpy; but there is no general agreement on the arbitrary temperature ranges used. Another frequent distinction is made between liquid dominated geothermal systems and vapor dominated systems.

Geothermal energy can be used for direct application, with a wide variety of end uses such as heating and cooling, industry, greenhouses, fish farming, and health spas [144]. While electricity production requires high temperature geothermal resources (over 100–150 °C) and implies drilling and pumping water from depth, direct application can use both high and low temperature geothermal resources and is therefore much more widespread in the world than electricity production. Indeed, the almost constant temperature of the soil few meters under the surface almost everywhere, can serve as a perfect heat source for small and simple heating and/or cooling systems driven by heat pumps.

In general, an assessment procedure should be used to determine the amount and the form of geothermal energy stored in the subsurface and these factors would restrict the type of application and extraction method [146].

Usually, the exploration program is developed on a step by step basis, closely following those of traditional fossil fuels search and exploitation. The initial phase is based on the selection of the most promising areas. The surface investigations in the selected area form the pre-feasibility phase, while the subsequent feasibility phase consists of deep exploratory drilling and reservoir testing. At an early stage in exploration, prior to drilling, resource assessment is largely qualitative. Once a few wells have been drilled, it will be possible to undertake a more accurate resource assessment. The final phases of the project are those of development and exploitation. During each stage of the process, the least interesting areas are gradually eliminated so that efforts are concentrated on the remaining, more promising ones.

A general approach to both targeting a geothermal well location and assessing resource capacity is to gather data about anomalies, and to define a conceptual model consistent with the available information.

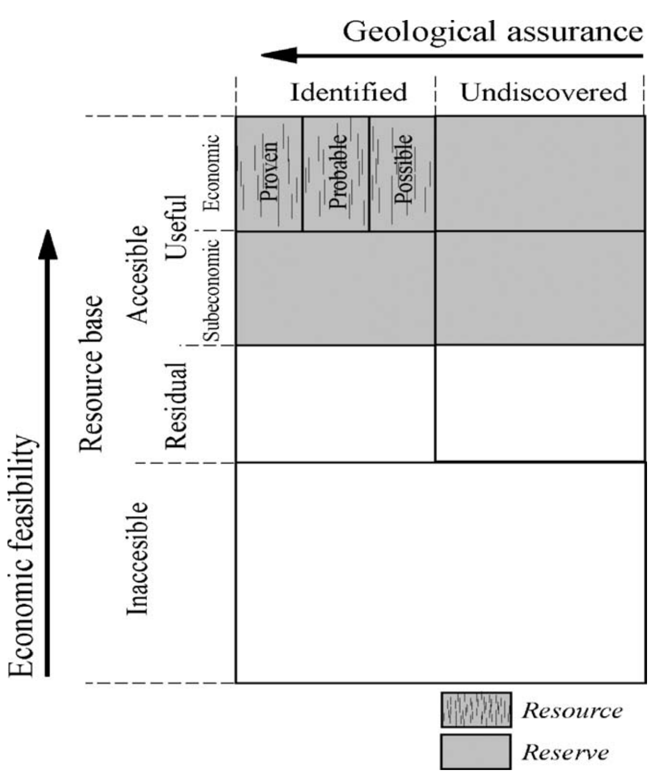

Fig. 7.1. Diagram representing the different categories of geothermal resources according to Muffler and Cataldi [145].

7.2. Geothermal exploration data

Once a geothermal region has been identified, various exploration techniques are used to locate the most interesting areas. These techniques are based on several surveys which collect data to estimate temperature, reservoir volume and permeability at various depths, as well as to predict whether wells will produce steam or just hot water [147].

Geological and hydrogeological studies provide basic information to define any exploration program. The presence and distribution of young volcanic rocks, active volcanoes, craters, calderas, faults and fractures are the main data used in the early stages of geothermal resource assessment, aiming to identify geothermal phenomena and to estimate the size of the resource. Geochemical surveys are a useful means of determining whether the geothermal source is water or vapor dominated. The chemical characteristics of the deep fluid can be interpreted as geothermometers, i.e. a set of experimental relations that allow to define the model of the reservoir and its physical characteristics, such as temperature, electrical conductivity, density, etc., starting from the measured concentration of some minerals. Other commonly used techniques to infer the temperature of the fluids are: direct current resistivity, transient electromagnetic (TEM), and magneto-telluric (MT) studies [148].

7.3. Data integration for targeting promising areas and well sites

The decision making process involved in locating prospective areas, recommended for further study or exploratory drilling, demands to combine, integrate and interpret the results of geological, geochemical, geophysical and other surveys [149]. GIS models have been successfully used in performing these tasks. They can be grouped according to their main goal: selecting promising geothermal fields for further exploration at regional scale or defining specific sites for well drilling at local/basin scale.

The methodologies used by Noorollahi et al. [150] and by Yousefi et al. [151] are quite similar and belong to the first group of studies. The datasets used in the analysis consist of geological, geochemical and geophysical information. Boolean integration method by using "or" and "and" operators were applied to combine all the evidence layers within each type of information, resulting in three suitability maps: geological, geochemical and geophysical (thermal). The final geothermal favourability map is then created by weighted overlay. Noorollahi et al. [150] also presents a distance relationship analysis to determine the predominant distance between actual geothermal wells and interesting geological features (such as faults or hot springs) represented in a GIS layer. The results are buffers around those known features that can be combined to obtain the final favorability map. Carranza et al. [152] focuses on the analysis of spatial distribution of geothermal prospects and thermal springs (evidences), and their spatial association with geological features (resources), highlighting their strong positive correlation. As a result, the mapping of high geothermal potential is presented. The methodology presented by Blewitt [174] also studies spatial relationships at regional scale, but between geologic structures and regional tectonic strain measured with GPS geodetic observations.

Table 7.1
Overview of estimated geothermal resources potential in the world [156].

	Lower limit for the potential of geothermal resources	World geothermal potential for identified resources	Upper limit for total world geothermal potential
Resources suitable for electricity generation	0.05 TW_e	0.2 TW_e	1–2 TW_e
Resources only suitable for direct use	1 TW_{th}	4.4 TW_{th}	22–44 TW_{th}
Total potential	1.5 TW_{th}	6 TW_{th}	30–60 TW_{th}

The final stage of a feasibility study is exploratory well drilling, and this is the only means of determining the real characteristics of the existing resource and thus assessing its potential. Several studies at local/basin scales have used GIS for the siting of exploratory wells in the most favorable areas. In the case reported by Prol-Ledesma [153], three knowledge driven models are proposed: Boolean logic model, index overlay model and fuzzy data analysis. In all models the same input data are used and the same conditions need to be satisfied. The Boolean method proved to be more restrictive and therefore more dependable for exploration well siting. Noorollahi et al. [149] introduce the results of an environmental suitability analysis (e.g. land cover, residential areas, etc.) to select the most promising well sites. As stated by Cumming [154], using a conceptual model approach in well targeting has the advantage of testing the properties of the model, especially for temperatures.

7.4. Resource conceptual model

Geothermal conceptual models bring together the observed and inferred information that best illustrates the reservoir fluid and rock properties. According to the volume method [145], the electric power generation potential from an identified geothermal system depends on the thermal energy in the reservoir, the amount of thermal energy that can be extracted from the reservoir at the wellhead, and the efficiency with which that wellhead thermal energy can be converted to electric power. The volume method was quickly established as the standard approach and most of the assessments made in parts of the United States rely on a version of this method. Nowadays, a new assessment of identified geothermal resources is being carried out by the U.S. Geological Survey, still using the volume method while incorporating some modifications regarding, among others, the temperature and depth ranges for electrical power production. For example, the assumed 150 °C lower limit for electric power production is under revision to include power production from moderate temperature systems using binary technology [155].

A more accurate assessment method is the use of geothermal simulation models to estimate the generation capacity of a given geothermal field. A detailed knowledge on the internal conditions of the geothermal reservoir is needed, and therefore, this method can hardly be applied until several wells have been drilled [156].

7.5. Geothermal resource assessments and maps

Stefansson [156] recently presented an estimation of the geothermal potential of the world. The volumetric assessment method on the identified resources was assumed to provide the most likely value, while the hidden resources were assumed to be 5–10 times than those identified and the results obtained by simulation models tended to be 4–5 times lower than the first method. The results are summarized in Table 7.1.

The geothermal resources of most European countries have been estimated and compiled in an atlas [146]. A volumetric heat content model was the basis for calculating the resources, assuming that exploitation would take place in a doublet system. Mapping of geothermal potential at regional scale have been implemented using GIS in many other countries ([157–159]).

7.6. Challenges for the near future

The utilization of geothermal energy has been limited to areas in which geological conditions allow a carrier liquid or steam to transfer the heat from deep zones, but only a small fraction of the geothermal potential has been developed so far, and there is ample space for an increased use of geothermal energy both for electricity generation and direct applications.

Most current studies on the classification of favorable areas have been based on GIS tools. However, technical improvements and innovative technologies, such as enhanced geothermal systems (EGS) and binary plants, offer new perspectives in this sector. EGS technology is based on developing new reservoirs through the creation and stimulation of fractures and thus it requires existing models of thermal energy recovery factors and resource assessment tools to be adapted. In addition, advances in power production technology and the scientific understanding of geothermal systems indicate that some important elements of geothermal assessment methodology require detailed examination and revision, which indeed makes the updating of geothermal assessment appraisals obligatory.

8. Conclusion

A survey of methods and tools to evaluate the availability of renewable resources (i.e., solar, wind, wave, biomass and geothermal energy) has been presented. In particular, potential, theoretical and exploitable energy have been differentiated and investigated for each kind of resource. All these energy sources share the feature of being distributed over the territory and of being measurable only at specific sites. This means that they all need tools to determine their spatial dimension and these may be provided by geostatistical tools or by remote sensed spatial information. In quite the same way, they all require GISs both to process data and to demonstrate their local impacts. Indeed, their presence on the territory generates some form of conflict with other uses, from the subtraction of land otherwise dedicated to food agriculture (as it happened in Mexico in 2007 with the famous "tortilla riot") or by perturbing existing landscapes (as claimed by various associations in UK). To correctly support decisions on renewable energy sources, studies should thus deepen the evaluation of these conflicts and take into account not just the exercise of the energy conversion plants, but their entire life-cycle. The University of Sydney's Integrated Sustainability Analysis report (see [160]), for instance, estimates at something between 20 and 40 kg CO_{2eq}/MWh, depending on the estimated life and capacity factor, the GHG emission due to the building, operating and decommissioning of wind turbines. "Renewable" does not mean "completely CO_2 neutral" and thus more detailed and comprehensive analysis tools will probably be developed in the near future.

An additional important issue (that has not been highlighted in the previous sections) is that none of the renewable source analysed would be able to supply the growing energy need of even small isolated areas of the world. It is thus necessary to integrate few of them and choose the best mix of different resources. The objective of choosing a mix of plants that maximizes environmental sustainability as well as economic viability can somehow be

conflicting with the maximization of the energy supply reliability. Methods and tools that deal with the this type of integration are already present in the literature. An example is HOMER computer model [161,162]: it is an easy to use tool that simplifies the task of evaluating design options for both off grid and grid connected renewable power systems for remote, stand alone, and distributed generation applications (https://analysis.nrel.gov/homer/). It comprises three different modules:

- a simulation module, at hourly time scale, that compares the electrical and thermal demand to the energy that a mixed renewable/fossil system can supply, and estimates the cost of installing and operating the system over the lifetime of the project. HOMER simulates system configurations with several different combinations of components, and discards all those that do not respect reliability or cost constraints;
- an optimization module: after simulating all the possible system configurations, HOMER orders feasible configurations from the most to the least cost effective, so that different design options can be compared;
- a sensitivity analysis module: that repeats optimization for different values of parameters to take into account uncertainties.

HOMER can thus find feasible solutions to design an efficient mix of renewable energy plants on the basis of a cost criterion. It could be easily expanded to consider other objectives such as land occupation or GHG reduction. Yet another research direction will emerge as extremely important in the near future: the management and control of a mix of existing plants, subject to an intermittent resource availability, that has to meet the fluctuating energy demands and be embedded into an energy network, particularly for electricity, that was originally conceived with a centralized structure. The energy flow may in fact reverse from the nodes to the center of the network and this may create tough problems to current devices. A large restructuring of the energy networks will probably be necessary in the future and this will entail the consideration of multiple objectives and multiple criteria, including the competition for land use. Examples related to design and planning decision problems, solved through mathematical programming and multicriteria approaches, can already be found in the literature at local scale (for example: [163–165]), but more flexible and integrated tools that couple environmental and decision models, databases and assessment tools, integrated under a GIS based Graphical User Interface (GUI) [166–168] are still necessary to implement Environmental Decision Support Systems that can operate on different territories and multiple scales to plan and manage an efficient mix of renewable energy sources.

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